
Do fast winds dominate the dynamics of planetary nebulae?

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1 Introduction

A review of recent observations of the kinematics of six objects that represent the broad range of phenomena called planetary nebulae (PNe) is presented. It is demonstrated that Hubble-type outflows are predominant, consequently it is argued that ballistic ejections from the central stars could have dominated the dynamical effects of the fast winds in several, and perhaps all, of these objects. An alternative possibility, which involves an extension to the Interacting Winds model, is considered to explain the dynamics of evolved planetary nebulae.

A consensus has been established (e.g. Kastner et al. 2003) about the basic processes for the creation of a planetary nebula (PN): an intermediate mass star (initial mass 1–8 M_{\odot}) loses mass in its Asymptotic Giant Branch (AGB) phase at $\leq 10^{-4} M_{\odot} \text{ yr}^{-1}$ by emitting a ‘superwind’ flowing at 10–20 km s^{-1} over $\leq 10^5 \text{ yr}$ (depending on the initial stellar mass). The star eventually becomes an 0.5–1.0 M_{\odot} White Dwarf (WD) which produces enough Lyman photons to ionise a substantial fraction of the circumstellar envelope recognisable as the expanding PN. The whole structure can be enveloped as well in a prior low density Red Giant (RG), similarly slow, wind. In the transition from the AGB to WD phase the outflow mass loss rate declines to $10^{-8} M_{\odot} \text{ yr}^{-1}$ but increases its speed dramatically to several 1000 km s^{-1} to blow as a fast wind for an as yet unknown period. As the WD star evolves further the fast wind declines.

Obviously the real story is hugely more complicated in detail and variable between objects (Balick & Frank, 2002). Morphologies range from simple, spherical shells to complex poly-polar structures (e.g. NGC 2440, López et al. 1998) probably around close binary systems. The ejected, dusty, AGB, molecular superwind material is often very clumpy (e.g. the cometary globules of NGC 7293, Huggins et al 1992; Meaburn et al. 1992; O’Dell & Handron 1996; Meaburn et al. 1998). High-speed jets (e.g. IRAS17423-1755, Riera et

al. 1995) and ‘bullets’ (e.g. MyCn 18, Bryce et al. 1997; O’Connor et al. 2000) are found and even shell or lobe expansion velocities can range from 20 km s^{-1} to $\geq 500 \text{ km s}^{-1}$ (e.g. He2-111, Meaburn & Walsh 1989 and NGC 6302, Meaburn et al. 2005c). Sometimes many of these distinctly separate phenomena occur in one object reflecting the separate stages of its complex evolution. The ages of observed PNe range from the initial proto-PN stage to those of well-evolved PN $\geq 10^4$ yr later around an ageing WD star.

In current dynamical theories of PNe much emphasis is placed on the importance, even dominance, of the fast wind. In the elegant interacting winds (IWs) model and its variants (Kwok, Purton & Fitzgerald 1978; Kahn & West 1985; Chu et al. 1993; Mellema 1995 & 1997; Balick & Frank 2002) the shocked ($10^6 - 10^8$ K) fast wind can form an energy-conserving, pressure-driven ‘bubble’ in the preceding smooth AGB wind whose density declines as distance $^{-2}$ from the star. This possibility is similar in principle to that pioneered by Dyson & de Vries (1972) albeit within a stationary medium of uniform density. The characteristic shell of a simple PN is consequently formed between the shocks in the fast wind and AGB wind and, being pressure-driven by the superheated gas, is expanding faster than this ambient AGB outflow. A variant would have the momentum of the isotropic fast wind simply sweeping up the AGB outflow and accelerating an expanding shell. For the creation of a bi-polar PN Cantó (1978) and Barral & Cantó (1981) considered something similar. Here a fast wind from a star embedded in a dense circumstellar disk forms cavities on either side of it which are delineated by stationary shocks across which the fast wind refracts to form bi-polar, momentum-conserving, outflows parallel to the cavity walls. Again, energy conserving, elongated ‘bubbles’, pressure driven by the shocked wind on either side of this disk, would also form expanding bi-polar lobes. Steffen & López (2004) examine the effects of the fast wind on a clumpy AGB wind which is more realistic than the smooth density distributions usually considered in the IWs models.

There is now an abundance of observational evidence that fast winds exist within PNe and some evidence that they interact significantly with the circumstellar envelopes. Patriarchi & Perinotto (1991) discovered that 60 percent of central stars of PNe emit particle winds of 600–3500 km s^{-1} . However, direct observational evidence of their interaction with the circumstellar medium is more limited. Collimated and truncated ablated flows, where the fast wind has mixed with, and is slowed by, photoionised gas evaporating from dense, stationary, globules (Hartquist et al. 1986; Dyson et al. 1989a; Dyson, Hartquist & Biro 1993) are detected in the hydrogen-deficient PNe A30 (Borkowski et al. 1995; Meaburn & López, 1996) and A78 (Meaburn et al. 1998). Also, diffuse X-ray emission is found in the cores of five PNe (NGC 7009, Hen 3-1475, BD+30deg 3639, NGC 6543 & NGC 2392 – Chu et al. 2001; Gruendl et al. 2001; Guerrero, Chu & Gruendl 2004; Chu et al. 2004; Guerrero et al. 2005). Similarly, Kastner et al. (2003) observed such diffuse X-ray emission in the core of the bi-polar PN Menzel 3 (Mz 3) and Montez et al. (2005) inside the main shell of NGC 40 which is a PN generated by a WR-type star. All of

these authors interpret the X-ray emissions to be the consequences of the collisions of the fast winds with the slower moving surrounding AGB winds. They suggest that conductive cooling is occurring for the temperatures of the hot gases emitting the X-rays are far lower than if simply generated by shocks in the fast winds at their measured speeds. Nonetheless, they imply that over-pressured ‘bubbles’ of super-heated gases are forming and driving the expansions of the ionised PNe shells as predicted by the IWs model.

The principal purpose of the present article is to examine, on the basis of observations made recently with the two Manchester echelle spectrometers (MES - Meaburn et al. 1984 and 2003), the part played by the fast winds in the creation of the well-evolved PNe, NGC 6853 (Dumbbell) and 7293 (Helix), the young PN, NGC 6543 and the outer lobes of the bi-polar (poly-polar) ‘PNe’ NGC 6302, Mz 3 and MyCn 18 for these are all recently observed examples of the range of circumstellar phenomena broadly designated as PNe.

2 The evolved PNe, NGC 6853 and 7293

Cerruti-Sola & Perinotto (1985) and Patriarchi & Perinotto (1991) failed to detect any fast winds of $\geq 10^{-10} \text{ M}_{\odot} \text{ yr}^{-1}$ from either of the central stars of NGC 6853 and 7293 in their IUE observations. This is not surprising for both stars are well into their WD phases with surface temperatures $\approx 10^5 \text{ K}$ (Górny, Stasińska & Tyłenda 1997; Napiwotzki 1999) and well past the transitions from their AGB to WD phases during which periods the fast winds are expected to blow. The question is, do the present morphologies and kinematics of these PNe depend critically on the previous emissions of fast winds if they in fact occurred? Observations of NGC 6853 are reported in Meaburn et al. (2005a) and of NGC 7293 in Meaburn et al. (2005b) in an attempt to throw light on this question. These should be combined with an appreciation of the complementary imagery for NGC 7293 of O’Dell (1998) and O’Dell, McCullough & Meixner (2004).

Some aspects of the ionisation stratification of NGC 6853 and 7293 can be appreciated in Figs. 1, 2 & 3 and of the corresponding velocity structure in Figs. 3 and 4a & b. Highly excited gas emitting He II lines is expanding slowly around both exciting stars. These central volumes are themselves both surrounded by faster shells of lower excitation emitting the [O III] lines. All are contained within outer and even faster expanding lowly ionized shells emitting the [N II] lines. For NGC 6853 the central He II volume ($0.38 \times 0.33 \text{ pc}^2$) is expanding at $\leq 7 \text{ km s}^{-1}$, the inner [O III] shell at 13 km s^{-1} and the outer ellipsoidal ($0.50 \times 0.67 \text{ pc}^2$) [N II] shell at 35 km s^{-1} . For NGC 7293 the central He II volume (0.21 pc diam.) is expanding at $\leq 11 \text{ km s}^{-1}$, the inner [O III] shell (0.25 pc. diam.) at 12 km s^{-1} and the outer [N II] structure (0.64 pc. across and shown in Meaburn et al. 2005b to be bipolar with an axis tilted at 37° to the sight line to give the characteristic helical appearance of NGC 7293) is expanding at 25 km s^{-1} . The deep images in Figs. 1 and

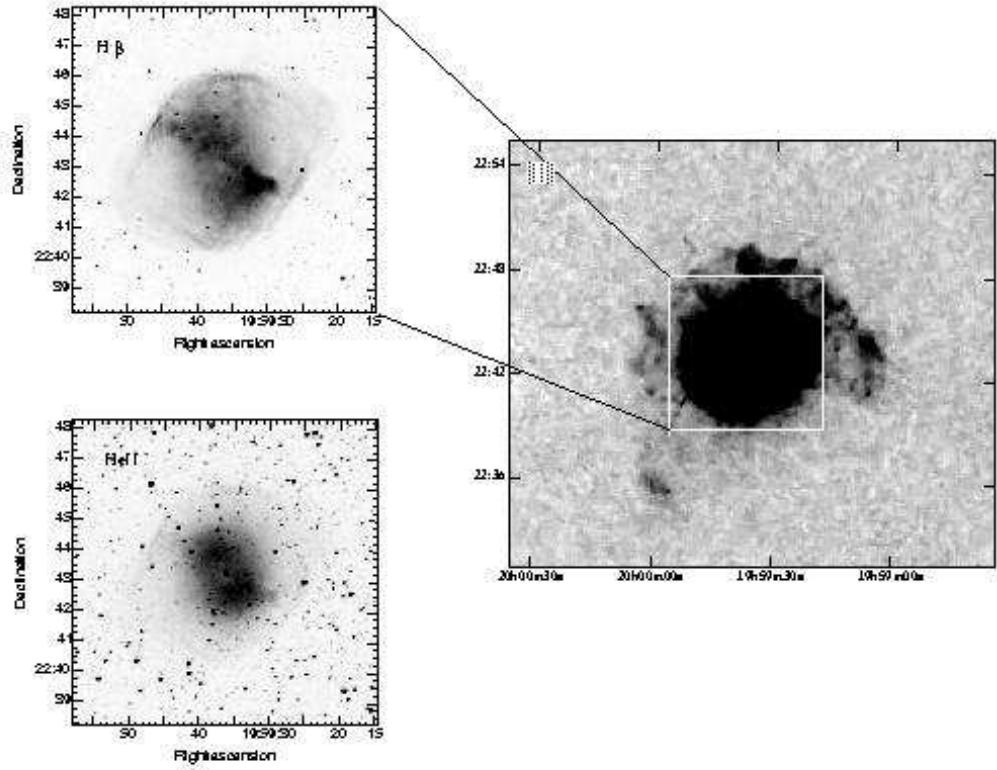


Fig. 1. A deep $H\alpha + [N II]$ image of NGC 6853 taken by Panos Boumis is compared with $H\beta$ and $He II$ 4686 Å images (compliments of Bob O’Dell) of the familiar ‘Dumbbell’ nebula (coords throughout are for J2000)

2 show the bright regions of both nebulae are surrounded by clumpy haloes which could be, within the IWs model, the as yet unaccelerated AGB wind but could alternatively be the prior RG wind.

Even if there were fast winds present in NGC 6853 and 7293 they could not reach the outer shells unless they percolated as mass-loaded flows through clumpy inner $He II$ and $[O III]$ emitting regions (Meaburn & White, 1982). However, with no current fast wind observed the IWs model could then only apply in the earliest post-AGB stages of the formation of these PNe i.e. the fast winds initially formed expanding bubbles then switched off. A somewhat elaborate consequence within the IWs model for an evolved PN could be the acceleration inwards of the inside surface of the outer shell, for it would no

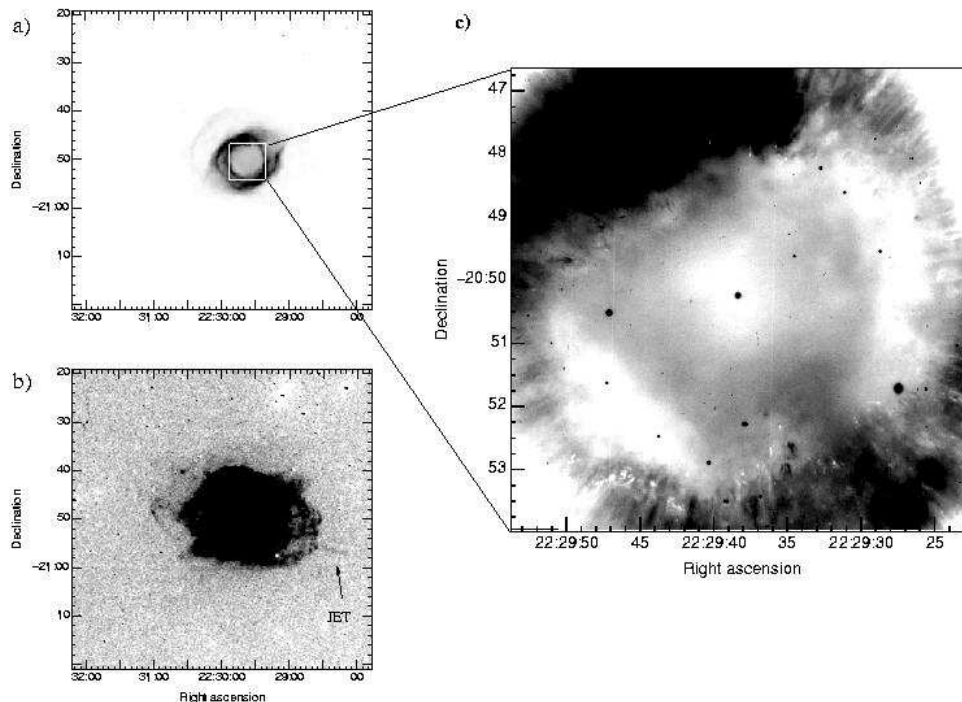


Fig. 2. The $H\alpha + [N II]$ image in a) shows the familiar, bright helical structure which gives the nebula its name ‘Helix’. It is shown in c) that this is enveloped in complex outer halos that may even include a jet. The NTT (La Silla) $[O III] 5007 \text{ \AA}$ image in c) reveals particularly well the inner $[O III] 5007 \text{ \AA}$ shell.

longer be supported by the over-pressure of the super-heated shocked gas, to cause the slower moving inner regions reported in Meaburn et al. (2005 a & b). The gap between the outer edge of the $[O III]$ inner shell and the inside edge of the $[O III]$ and $[N II]$ outer shell (Fig. 2) is not simply explained by this inward acceleration model.

Alternatively, the fast wind never existed or was ineffective over the long term. The expanding shells could then simply be pulsed, higher speed, ejections of AGB wind (for not understood reasons). The dynamical ages of the central $He II$ volume, the inner $[O III]$ and the outer $[O III]$ plus $[N II]$ NGC 7293 shells are all $\approx 10^4$ yr and the central $He II$ volume and outer $[N II]$ shell of NGC 6853 ≈ 8000 yr. Within this situation, in each PN, all of these emitting regions would have been ejected at about the same time but with decreasing velocities i.e. Hubble-type outflows. The haloes of NGC 6853 and 7293 could still be the prior, but lower speed, AGB or even RG winds emitted over $\geq 10^5$ yr.

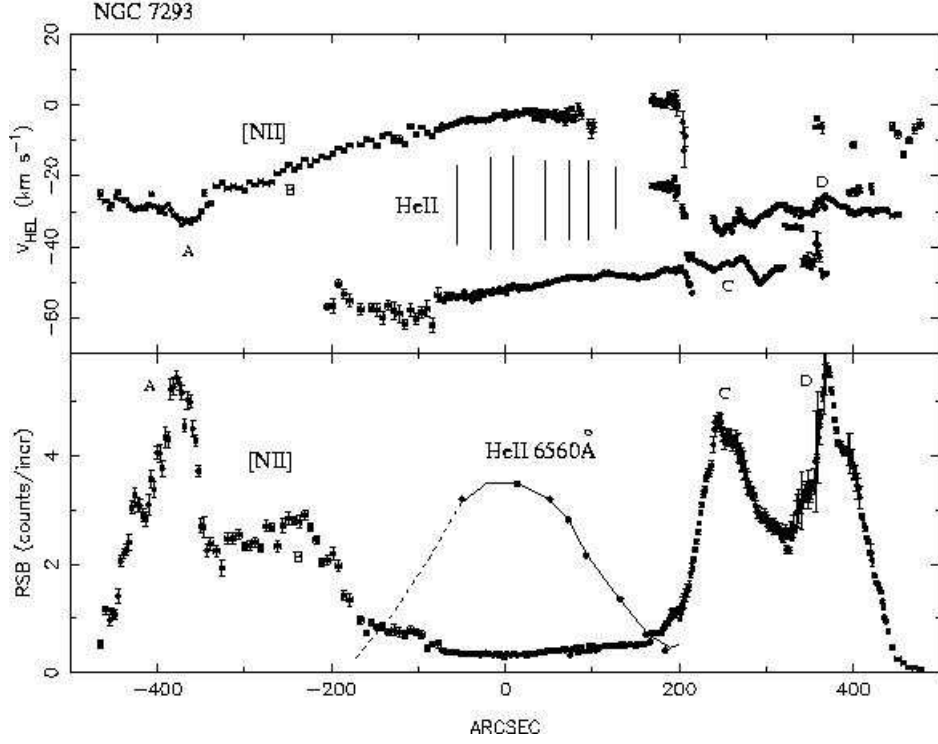


Fig. 3. In the top panel the radial velocities of separate velocity components in the [N II] 6584 Å profiles along an EW cut through the central star and over the helical structure in Fig. 2a are compared with the widths of single Gaussians that simulate the He II 6560 Å profiles around the nebular core. The latter have been corrected for instrumental broadenings. The relative surface brightness (RSB) variations of the [N II] 6584 Å and He II 6560 Å profiles are shown in the bottom panel along the same cut. The brightness peaks A-D over the helical structure are marked.

A comment must be made about the tails of the cometary knots in NGC 7293. As the fast wind is currently not observed in this PN it cannot be the cause of these radial tails. An alternative remains that dense knots in the AGB (or even RG wind) seen initially as SiO maser spots (Dyson et al. 1989b) are overrun by a pulse of AGB wind to draw these tails out.

3 The young PN, NGC 6543

The ‘Cat’s Eye’ nebula, NGC 6543, is a young PN photoionised by an O7+WR-type star which emits a high-speed particle wind at 1900 km s⁻¹ (Patriarchi & Perinotto, 1991). Its bright filamentary core is complex but within an overall 25 arcsec × 17 arcsec ellipse ($\equiv 0.12$ pc × 0.08 pc for a distance of $1001 \pm$

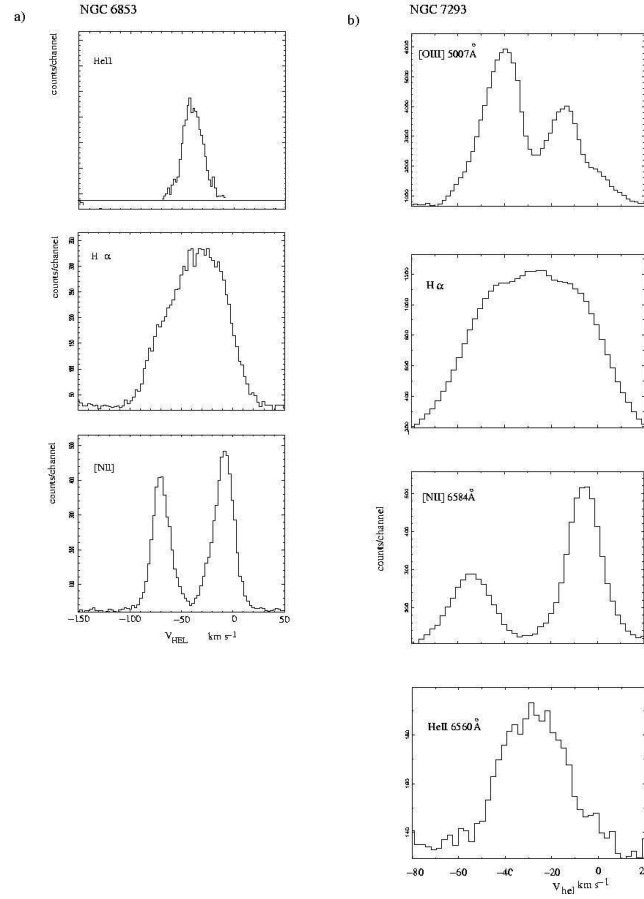


Fig. 4. a) Line profiles over the core of NGC 6853 are compared. c) As for a) but for NGC 7293.

269 pc as given by Reed et al. 1999). This core is surrounded by a highly filamentary structure, 330 arcsec diam. ($\equiv 1.6$ pc and see the image by Romani Corradi in Mitchell et al. 2005). Chu et al. (2001) have shown conclusively that diffuse X-ray emission is confined within an ‘inner’ ellipse of optical line emission, with a minor axis of 8 arcsec across, itself embedded in the larger bright core. Miranda and Solf (1992) had shown that this inner elliptical feature is expanding at 16 km s^{-1} to give a dynamical age of 2400 yr. The fast wind must therefore be confined to this small inner region. The larger filamentary features in the core, which surround this inner ellipse, and the bi-polar jets, seem independent of the presence of the fast wind and are most likely ejecta.

Bryce et al. (1992) had demonstrated that the outer, high excitation, halo is very inert i.e. expanding globally at 4.5 km s^{-1} which gives it a dynamical age of $1.7 \times 10^5 \text{ yr}$. Mitchell et al. (2005) show that all of the flows off globules in this halo are around the sound speed and therefore are solely a consequence of ionisation fronts created by photoionisation. There is no evidence of any interaction with the fast wind which must be confined to the inner ellipsoidal shell within the nebular core.

It is concluded that the post-AGB phase started only around 2400 yr ago and that a small shell, predicted by the IWs model is being driven by the fast wind into an extremely clumpy AGB wind, with maybe the outer halo even being the slow moving relic of the most recent RG wind. If the fast wind were to blow for 10 times its present age it is difficult to visualise the creation of a large expanding shell in such a clumpy outer halo.

4 The bi-polar PNe, NGC 6302, Mz 3 and MyCn 18

These bi-polar nebulae must have more complicated stellar systems than NGC 6853, 7293 and 6543 and as well have circumstellar disks. Here, following Bains et al. (2004), Smith (2003) and Smith & Gehrz (2005), they are designated PNe for they have, arguably, post-AGB elements in their nature although the central stars are most likely close binaries.

4.1 NGC 6302 – a high excitation poly-polar PN

NGC 6302 (PN G349.5+01.0) is a poly-polar planetary nebula (PN), which was described and drawn as early as 1907 by Barnard. It is in the highest excitation class of PNe with a central O VI-Type White Dwarf and possible binary companion (Feibelman 2001). This stellar system is heavily obscured by a dense circumstellar disk (Matsuura et al. 2005).

The kinematics of the prominent NW lobe of NGC 6302 (Fig. 5) have been determined in detail by Meaburn & Walsh (1980) and most recently by Meaburn et al. (2005c) – see examples from the latter in Fig. 6. Meaburn & Walsh (1980) showed ‘velocity ellipses’ in the position-velocity (PV) arrays of line profiles across the diameter of the lobe (as sketched in Fig. 7b and see Meaburn et al. 2005c) showed that this outflow is Hubble-type reaching $V = 600 \text{ km s}^{-1}$ at the extremities of the lobe (Figs. 6b & c). A ‘spot’ value of $V = 263 \text{ km s}^{-1}$ at position A’ in Fig. 5 (1.71 arcmin from the star) is shown in Fig. 7c. No fast wind has been directly observed (Feibelman 2001) from the O VI-Type WD star and its possible companion. For an expansion-proper motion distance of $1.04 \pm 0.16 \text{ kpc}$ (Meaburn et al. 2005c) the dynamical age of the lobe is 1900 yr.

It is concluded in Meaburn et al. (2005c) that an eruptive event 1,900 yr ago created the prominent NW lobe and possibly many of the other lobes.

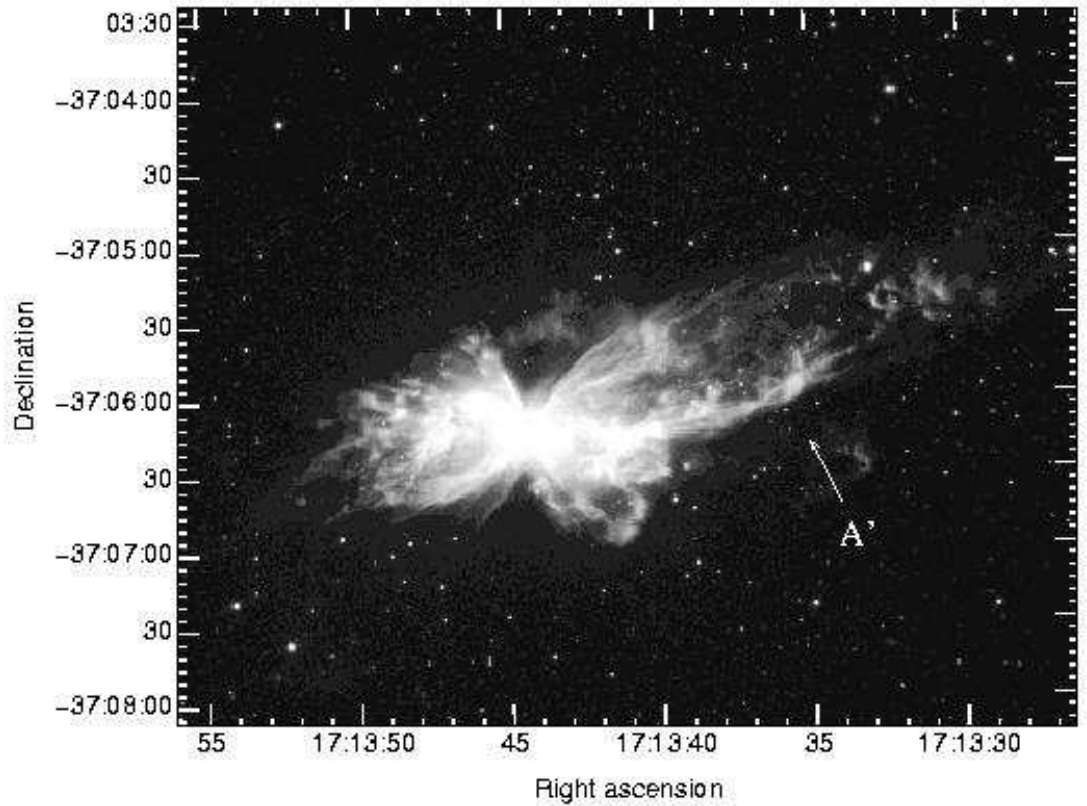


Fig. 5. An $H\alpha + [N II]$ image of NGC 6302 taken by Romani Corradi with the 3.6-m La Silla telescope. The cut A' shown in Fig. 7 is marked.

4.2 Mz 3 – a symbiotic PN

Bains et al. (2004) and Smith (2003) suggest that the central stellar system of the PN, Mz 3, (Fig. 8) is a symbiotic binary. López & Meaburn (1983) had shown that the bright central bi-polar shells of Mz 3 (the 9 arcsec diam. N shell and 14 arcsec diam. S shell in Fig. 8) are in spherical expansion at 40 km s^{-1} and 55 km s^{-1} respectively. For a distance to Mz 3 of 1.3 kpc (see Bains et al. 2004 for a review of possible distances) a mean dynamical age of 1435 yr for these inner shells is implied. These shells are on either side of a dense disk (Meaburn & Walsh 1985) which obscures the central stellar system.

Furthermore, Meaburn & Walsh (1985) revealed that the N and S lobes in Fig. 8 had circular sections, for velocity ellipses occurred in the PV arrays of

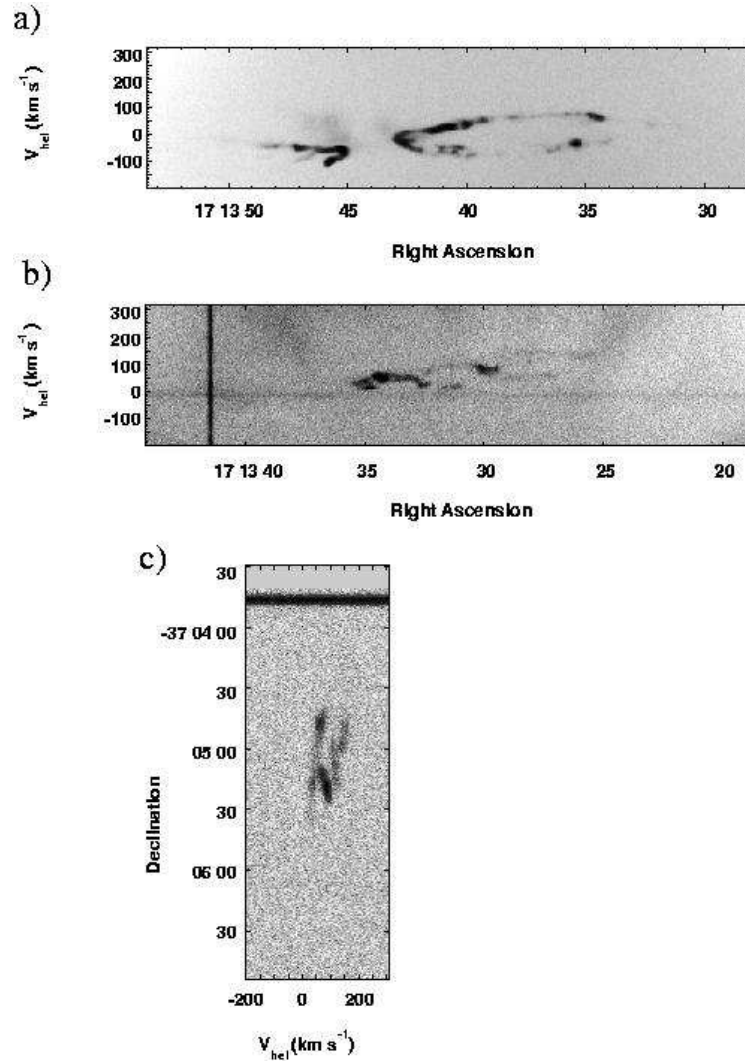


Fig. 6. Sample PV arrays of [N II] 6584 Å line profiles over NGC 6302 are shown. Those in a) and b) are for an EW slit centred on DEC -37 05 50 and -37 05 02 respectively. That in c) is a NS slit centred on RA 17 13 28. By comparison with the image in Fig. 5 it can be seen that the arrays in b) and c) cover the extremities of the prominent NW lobe of NGC 6302.

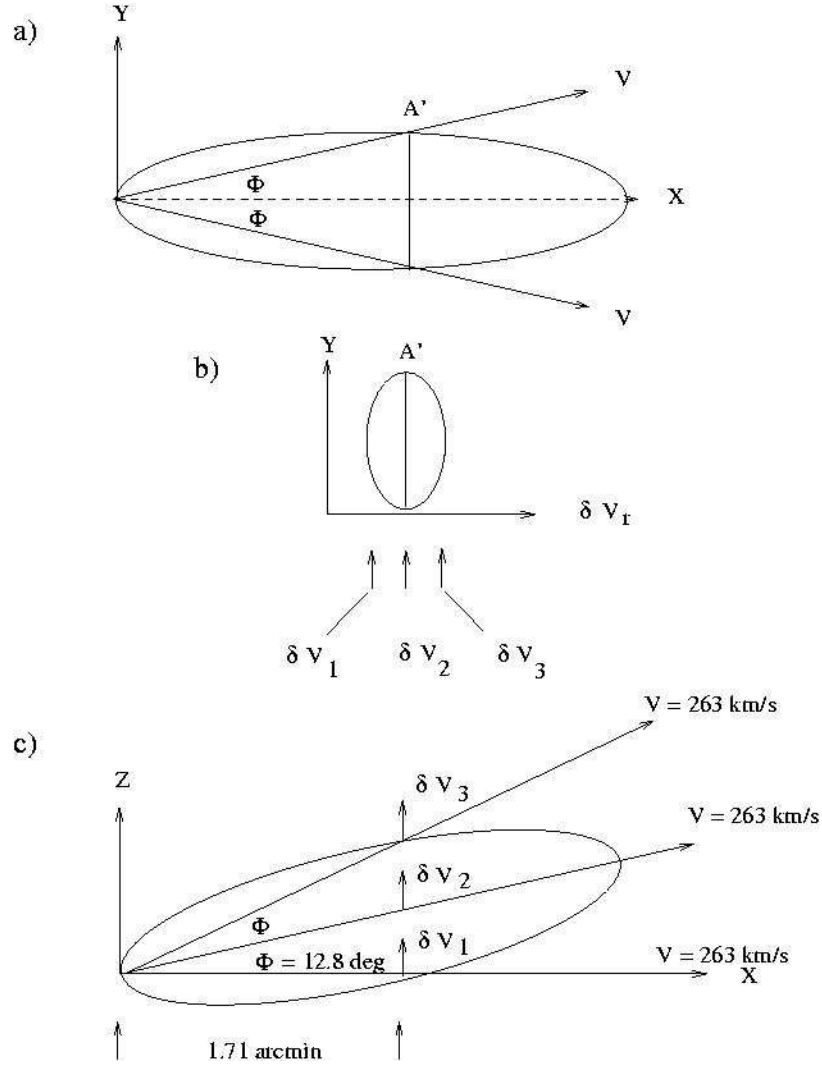


Fig. 7. The image of the NW lobe of NGC 6302 is shown schematically as an ellipsoidal structure with circular section in a) where X and Y are in the plane of the sky. The expansion velocity V is shown to be Hubble-type. The velocity ellipse found along cut A' (1.71 arcmin from the central star) in Fig. 5 is from Meaburn & Walsh (1980) and gives the parameters shown in c) where the Z dimension is perpendicular to the plane of the sky (the observer is below c). With Hubble-type expansion, $V \approx 600 \text{ km s}^{-1}$ at the extremity of the NW lobe (see Fig. 6b).

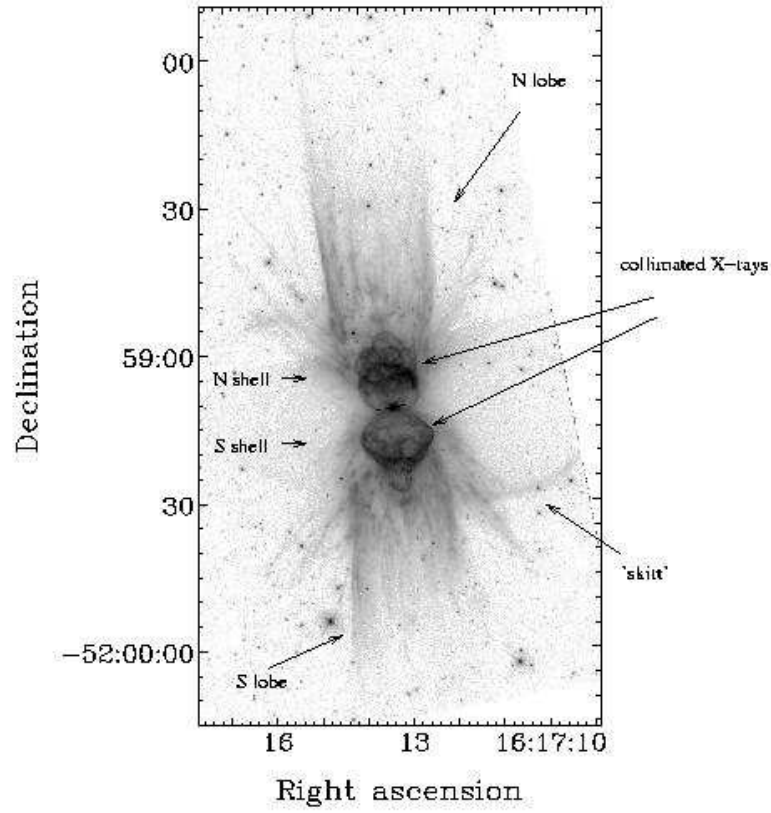


Fig. 8. An HST image of Mz-3 in the light of $H\alpha + [N II]$. The N and S lobes exhibit Hubble-type outflows and the central bright shells, N and S shell, contain diffuse X-ray emission though collimated along the lobe axis. The high speed ‘skirt’ identified by Santander-Garcia et al. (2004) is marked.

line profiles over their diameters, and that their outflows at velocity V along vectors directed away from the central star (as for NGC 6302 in Fig. 7 though with different angles) are very similar to those of NGC 6302 and similarly Hubble-type. Spot values of V at 20 arcsec N and S of the central star are given by Meaburn & Walsh (1985) as 90 and 93 km s^{-1} respectively. As for NGC 6302 (Sect.3.1) the Hubble-type nature of the outflows implies that at the limits of detection of these lobes (82 arcsec N and 52 arcsec S) V reaches 369 km s^{-1} and 242 km s^{-1} respectively as confirmed by Santander-Gracia et al. (2004). The corresponding dynamical ages for the N and S lobes of Mz 3

are consequently 1317 and 1273 yr respectively which are remarkably similar to those of the N and S shells.

The implication is that *all* of the outflows of the N and S shells and the N and S lobes are within a general Hubble-type velocity system which reinforces the possibility that they are all the consequence of ejections at closely similar times but with different ejection speeds. In any case the fast wind must be contained within the N and S shells to shield the N and S lobes from any direct interaction. Furthermore, the X-ray emission (Kastner et al. 2003) suggests that this fast wind is collimated along the bi-polar axis of Mz 3 and is causing the secondary protusions at the apices of the N and S shells evident in Fig. 8. This would preclude the N and S shells themselves from being ‘bubbles’ driven only by this fast wind.

Incidentally, the high-speed skirt (Fig. 8) has been properly identified by Santander-Garcia et al. (2004) as the origin of the high-speed ‘velocity ellipse’ in the PV arrays of Meaburn and Walsh (1985) and the high-speed feature in Redman et al. (2000).

4.3 MyCn 18 – a nova-like PN

MyCn 18 is also aptly known as the ‘Engraved Hourglass’ nebula due to the visually dramatic bipolar appearance of its bright core (Sahai et al. 1999 and references therein). However, interest in MyCn 18 has recently been further heightened by the discovery of the knots of ionized gas flowing in both directions along its bipolar axis at speeds of up to 660 km s^{-1} (Bryce et al. 1997; O’Connor et al. 2000). These can be seen in the continuum subtracted image in Fig. 9a. Corradi & Schwarz (1993) had previously investigated the bright core of MyCn18 and concluded that it is a young PN. The presence of a dusty, molecular, equatorial waist region, suspected by Sahai et al. (1999) on the basis of an excess in the stellar K-band photospheric flux, substantiated this young age. The radio thermal emission map of Bains & Bryce (1997) reveals the ionised inside surface of the dense waist region to be very bright in comparison to emission from polar directions.

The Hubble-type nature of the knotty outflow is clear in Fig. 9b (from O’Connor et al. 2000). It is notable that the best fit straight lines are significantly displaced from the systemic radial velocity near the nebular core. O’Connor et al. (2000) show that these knots were ejected over a 300 yr period with a dynamical age of 1250 yr (Bryce et al. 1997). They also conclude that dynamically, the most plausible explanation seems to be that the high speed knotty outflow from MyCn18 is the result of a (possibly recurrent) nova-like ejection from a central binary system. This is in harmony with the considerations of Sahai et al. (1999) who favour a close binary system to generate the morphology of the very innermost regions of MyCn 18. In these circumstances the knots would be the manifestation of ballistic, dense, bullets ejected with a range of speeds and not the consequence of acceleration by a fast wind.

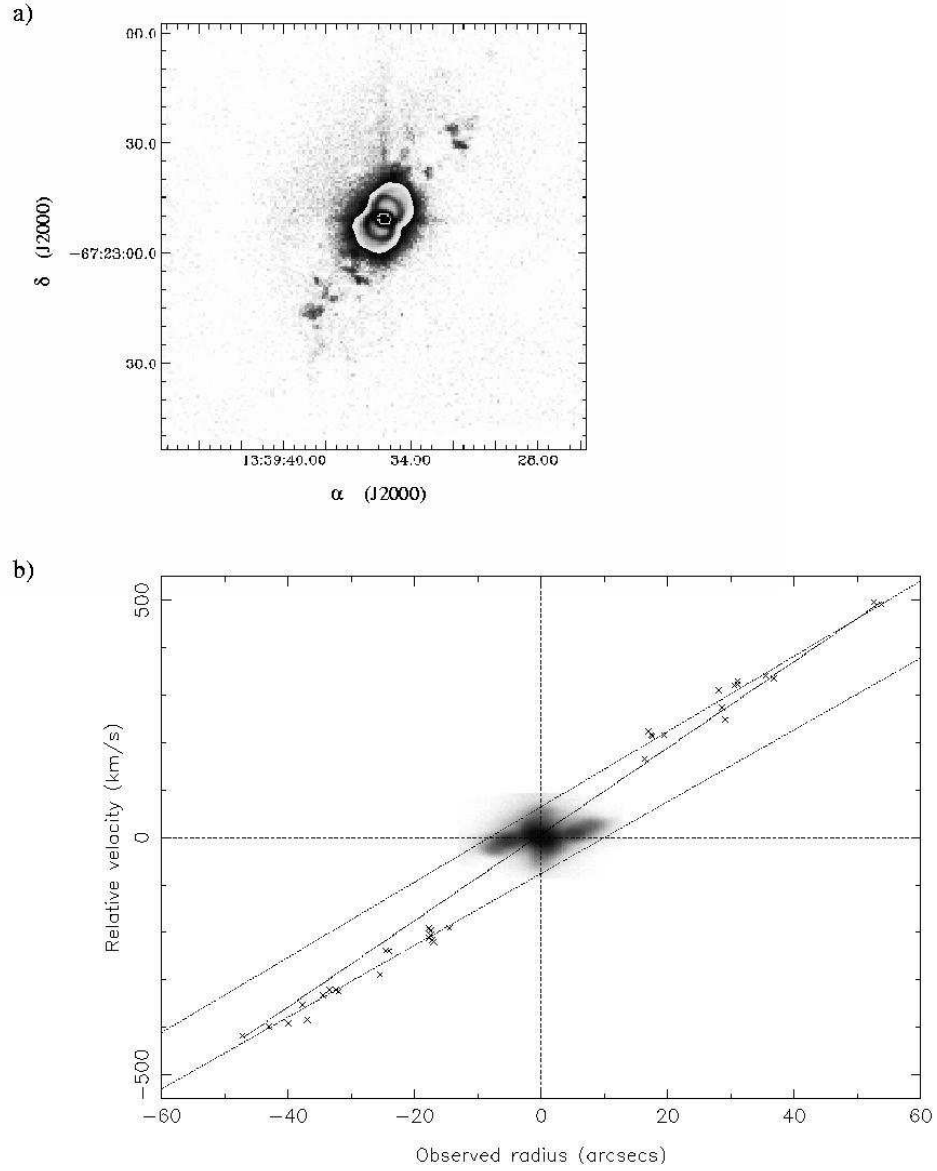


Fig. 9. In a) the image of the bright core of MyCn 18 taken with the AAT (Bryce et al. 1997 and O'Connor et al. 2000) is shown compared with the faint knots along the lobe axis. In the PV diagram in b) the relative radial velocities of these knots are shown as crosses. Very high-speed, Hubble-type, bi-polar motions are indicated for the radial velocities follow straight lines.

5 Conclusions

The IWs model certainly seems applicable to the very innermost shell of the young PN NGC 6543 (and very clearly to the main shell of NGC 40 – see Sect. 1). However, considerable modification of this theory is needed to explain the current state of the evolved PNe, NGC 6853 and 7293. The fast wind could have switched off well before the 10^4 yr age of their expanding shells generating an inward acceleration of their inside surfaces. Alternatively, it remains possible that eruptive events over 10^4 yr have dominated any effects of the fast winds, active only for a few thousand years in these PNe, to create the Hubble-type expansions throughout their volumes that are currently observed.

The preponderance of Hubble-type outflows of the lobes of the bi-polar PNe, NGC 6302, Mz 3 and MyCn 18 (and see Corradi 2004 for other examples) invites the simplest interpretation; that they are consequences of ejections over short periods of time but of material with different speeds. Even when a fast wind is currently present (e.g. Mz 3) the outer high-speed lobes are shielded from it by inner shells.

The present article has been deliberately limited to considering the dynamics of a small number of objects whose motions have been well observed. It seems clear in this small sample that simple ballistic ejections, maybe involving close binary systems in some cases, could dominate the dynamical effects of the fast winds.

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